Understanding the Origin and Evolution of Jenolan Caves: The Next Steps

R. Armstrong L. Osborne

Faculty of Education and Social Work, A35, The University of Sydney, NSW 2006
armstrong.osborne@sydney.edu.au

Osborne, R.A.L. (2014). Understanding the origin and evolution of Jenolan Caves: the next steps. *Proceedings of the Linnean Society of New South Wales* 136, 77-97.

The dating of cave and surficial sediments by Osborne et al. (2006) indicated that some sections of Jenolan Caves, particularly the large chambers, formed in the Early Carboniferous before deposition of sediments dated at 340 Ma. The dating also identified younger mass-flow sediments, dated at 303Ma and secondary fine illite, dated at 258 Ma and 240 Ma indicating burial of the caves under the Sydney Basin. These dates meant that a new chronology for cave development at Jenolan is required to supersede that of Osborne (1996b). Construction of this chronology raises new questions: Did the paragenetic conduits form before deposition or after stripping of the Sydney Basin? Caymanites (marine carbonate turbidite palaeokarst) appear to be older than 340 Ma, but does this make palaeogeographic sense? The Early Carboniferous dates give us a beginning for the history of the present caves at Jenolan, but much of the story is missing. Many obvious features in the caves have not been studied. Present knowledge of the developmental history, palaeokarst and sediment stratigraphy, morphology and mineralogy of tourist caves at Jenolan Caves is insufficient to support sound conservation, management, development and interpretation. The next step in understanding Jenolan Caves is a structured program of dating, geological, mineralogical and geomorphic studies.

Manuscript received 17 July 2013, accepted for publication 11 December 2013

KEYWORDS: cave sediments, dating, Jenolan Caves, palaeokarst, speleogenesis

INTRODUCTION

Despite the popularity of Jenolan Caves, there was very little study and very little was written about the origin and evolution of the caves prior to the publication of my synthesis (Osborne, 1999b). Sussmilch and Stone (1915) speculated on the age of the caves while Taylor (1923, 1958) attempted to correlate cave development with that of the Blue Mountains landscape using a fluvial model of cave development. In the numerous editions of his guidebooks Dunlop (1979) noted the role of solution, cracks and the three streams passing through the limestone in cave development. Beginning in 1983 I started a new study of Jenolan Caves, at first concentrating on palaeokarst and the geological record of cave development.

During the 1990s it became clear that while the palaeokarst made sense, the morphology of the caves themselves made little sense, particularly if they were conventional stream caves as had been generally accepted. After visits to Slovenia and Hungary in 1997, I realized that much of what we see at Jenolan is quite unlike the text-book stream caves of Slovenia, but the large dome-shaped chambers such as the Temple of Baal have similarities with features seen in the hydrothermal caves of Budapest. Looking at the caves in a new light I saw both bottom up and paragenetic features, which resulted in my first attempt at putting the story of cave development at Jenolan together (Osborne, 1999b).

Assumptions and definitions

In this paper I make certain assumptions about the origin and evolution of Jenolan Caves and use some terms in particular ways. Firstly, my basic premise is that Jenolan is a multiphase / multi-process cave system, which means that:

1. Caves have formed several times in the 400 Ma history of the Limestone.
2. Some old caves are filled with lithified sediment and are now intersected by younger caves. I restrict the use of the term *palaeokarst* to these sediments and the features they fill.
3. Some caves contain very old sediment contained within the same cave walls that delimit the open cavities that it is possible for humans to enter today. I call these deposits *relict* sediments. I do not use the term palaeokarst to apply either to these sediments or to the cavities they fill even though they may the hundreds of millions of years old.
4. There are no simple answers to the questions "How old are the caves?" and "How did the caves form?" as different sections of the accessible and palaeokarst caves formed at different times and by different processes.

Secondly, following Bella and Bosák (2012), I have abandoned the use of the terms hypogene and hydrothermal except where there is direct evidence that hot water or water with a deep-sourced aggressive agent is responsible for speleogenesis. In cases where there is morphological evidence that a cave has been excavated by rising water of unknown composition I use the term *per-ascensum.*

METHODS

Morphology

Caves are underground landforms, so just like surface landforms their gross morphology (seen by visual observation, in plans and in long and cross-sections) and their macro-morphology (seen in the rock forms in the caves called speleogens) should provide evidence for their mode of formation. In the case of Jenolan the pattern of cave development is strongly influenced by the shape and geological structure of the limestone mass with passages north of the Grand Archway following the general NNW-SSE strike of bedding and cleavage and south of the Grand Archway ("1" in Figure 1A) having a more N-S orientation following a change in strike (Figure 1A).

In long-section (Figure 2) it can be seen that while most of the cave development is horizontal, there are specific zones of vertical cave development spaced at apparently regular intervals along the length of the cave. Osborne (1999a) recognised that fluvial cave cross-sections in most textbooks showed sections of caves in horizontally bedded limestone (Figure 3A) and that cave cross-sections in almost vertically-dipping limestone like Jenolan would be different (Figure 3B) and that paragenetic conduits in vertically-dipping limestone would have a distinctive cross-section (Figure 3C).

Three types of large solution cavities at Jenolan can be identified on the basis of their gross morphology; *per-ascensum* cupolas such as those in the Mud Tunnels ("1" in Figure 1B, Figure 4A), paragenetic conduits, such as that north of the Pool of Reflections in River Cave ("2" in Figure 1B, Figure 4B) and fluvial streamways such as the Flitch of Bacon ("2" in Figure 1A, Figure 4C).

Morphostratigraphy

In caves like Jenolan where there have been several distinct phases of cave development it is possible to observe crosscutting relationships between one cavity type and another. Recognising these relationships can be a difficult and confusing exercise, but should allow the relative ages of different groups of cavities to be determined.

Sedimentology and Stratigraphy

Cave sediments can only be deposited after a cave has formed and surface-derived sediments can only enter a cave when an open pathway to the surface exists. The age of the oldest sediment in a cave gives the *minimum* age for the cave. The age of the bedrock is the maximum age of any cave.

Figure 1 (NEXT PAGE)

A: - Plan silhouette of the Jenolan Show Caves courtesy of Alan Warild, Jenolan Survey Project. (1) Grand Archway; (2) Flitch of Bacon; (3) Temple of Baal;(4) Wilkinson Branch; (5) Katie's Bower, Chifley Cave; (6) Exhibition Chamber, Lucas Cave; (7) Drain adjacent to Binoomea Cut; (8) Ribbon Cave; (9) Jubilee Cave; (10) Pool of Cerberus Cave;

(11) Cathedral, Lucas Cave; (12) Bone Box, Imperial Cave; (13) Imperial Streamway;

(14) Raft deposit in Imperial Cave (15) The Mystery, Chifley Cave.

B: - Detail plan of River Cave area, omitting Temple of Baal, Orient Cave and related cavities, courtesy Alan Warild, Jenolan Survey Project. (1) Mud Tunnels; (2) North of Pool of Reflections; (3) Olympia Stairs; (4) Orient Stairs; (5) South of Olympia;

(6) T Junction; (7) Northern extension of Mons Meg Loop; (8) The Ladder; (9) Mossy Rock.

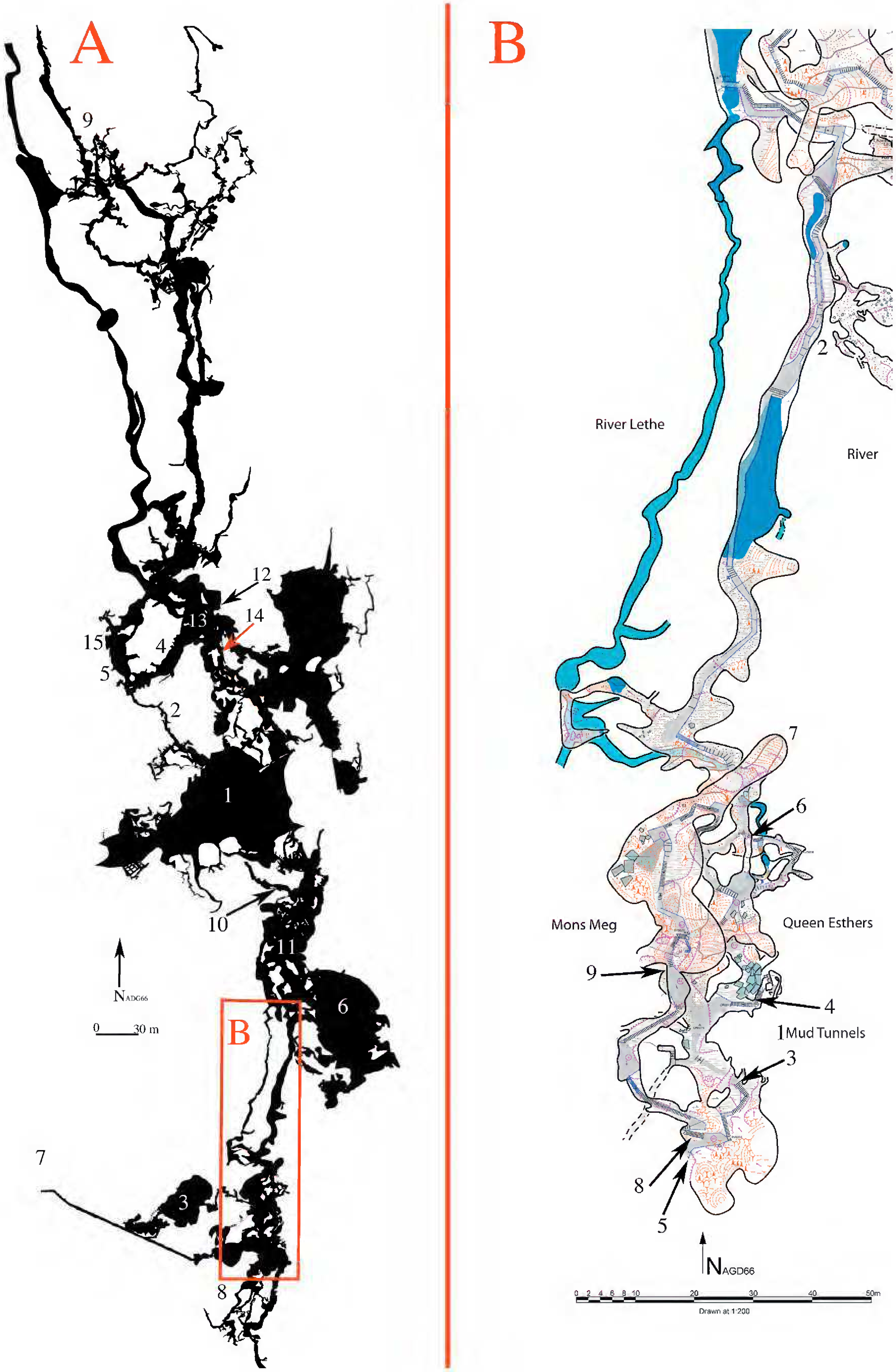
A
9
12
14
13
15
4
5
2
1
10
11
6
B
7
3
8
N ADG66
0 30 m
B
River Lethe
River
2
7
6
Mons Meg
Queen Esthers
9
4
1 Mud Tunnels
3
8
5
N AGD66
0 2 4 6 8 10 20 30 40 50m
Drawn at 1:200

Figure 2, Long Section, looking east, of the Jenolan Show Caves courtesy of Alan Warild, Jenolan Survey Project. Note regularly spaced high points B-H mostly cupola swarms, separated by zones of generally horizontal development A = Grand Archway, B = Cathedral, Lucas Cave, C = Baal-Orient System.

The grainsize and texture of cave sediments and the sedimentary structures in them are good indicators of the environment in a cave at their time of deposition. Sand, small rounded pebbles, ripples and imbricated cobbles are good indicators of fluvial conditions. Mud, finely laminated and graded-bedded layers and crystal raft deposits are indicative of a lacustrine environment while mixtures of cobbles, gravel and mud, without sand are indicative of mass flow deposits.

Palaeokarst features and deposits are evidence for the existence of caves in the past. Features with bedding or other geopetal structures oriented to the present horizontal must have formed after the last folding event. Cave sediments and palaeokarst deposits are difficult to date and can have very complex stratigraphy (Osborne, 1984). This can lead to the situation where even when an event is dated, it can be of little help in understanding the age relationship between major events assumed to be younger or older.

Correlation

Ideally, it should be possible to correlate both cave sediments and cave morphology with the known geological and geomorphic history of the strata and landscape in which a cave has developed. For instance, incision events in the surface landscape should correlate with incision and watertable lowering in the caves. Erosion and deposition at the surface, should, if there is a surface connection, correlate with deposition in the caves. Major events in regional geological history such as folding, granitic intrusion and burial should also leave their mark in the caves. In eastern Australia, however, correlation between the caves and geological and geomorphic history has proved to be neither simple nor uncontroversial (Osborne, 2005, 2010). In the case of Jenolan, the more we know, the more difficult some of the correlation seems to become.

THE INITIAL SYNTHESIS

In my 1999 Presidential Address to the Linnean Society of NSW I presented the elements of a synthesis and a framework chronology for the origin of Jenolan Caves. This recognized ten phases of cave development; five phases represented by ancient caves and palaeokarst deposits filling them, and five phases identified by the morphostratigraphy of and the sediments found in the presently open caves themselves, Table 1, below.

This chronology was largely based on observations made in the southern show caves, which proved to be more easily interpreted that those to the

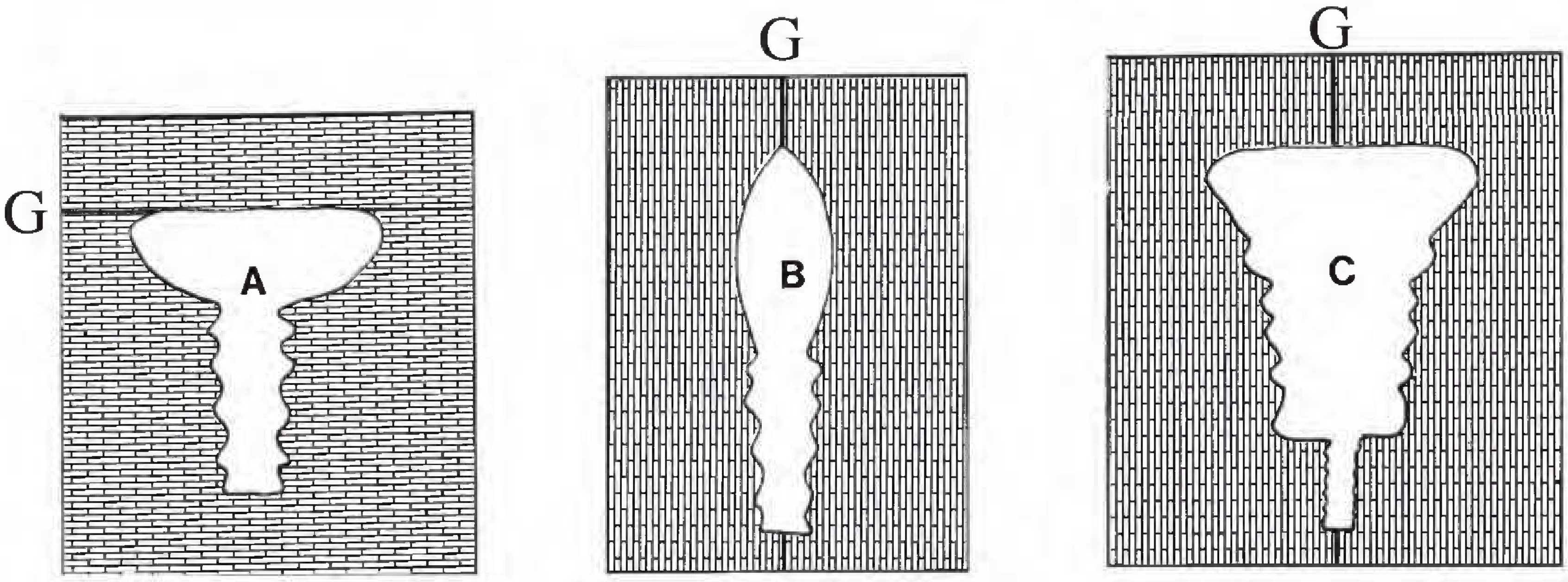

Figure 3, Passage cross-sections after Figure 17 of Osborne (1999a). (A) Textbook section of fluvial cave, upper part of profile phreatic, developed below horizontal guiding joint or bed "G"; lower part vadose canyon; (B) Cavity with similar origin to that in A, but developed along vertical guiding joint or bed "G". Note that vadose canyon is unchanged from "A"; (C) Cross-section of a paragenetic conduit developed in vertically dipping limestone modelled after cross-section of passage at "2" in Figure 1B.

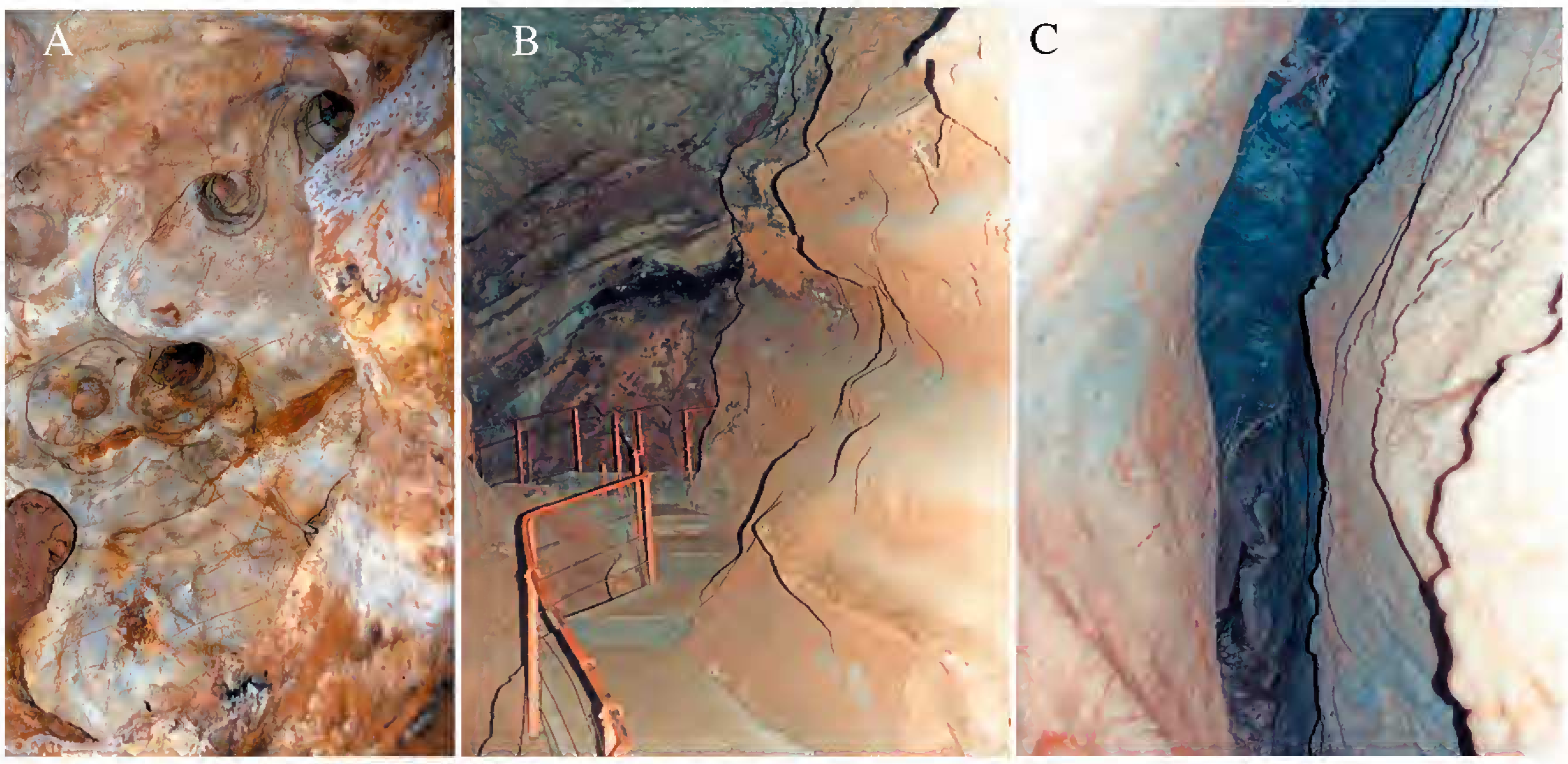

Figure 4, The three main cavity morphotypes of Jenolan Caves. (A) Per-ascensum, ceiling cupolas in the Mud Tunnels, River Cave, "1" in Figure 1B; (B) Paragenetic, paragenetic conduit north of the Pool of Reflections, River Cave, "2" in Figure 1B, looking north. Note rising and falling notches in eastern wall; (C) Fluvial, meandering vadose canyon, The Flitch of Bacon, Chifley Cave, "2" in Figure 1A. View looking up to cave ceiling.

north of the Grand Archway. As no absolute dates had been determined for either the clearly ancient material or for the unconsolidated sediments in the caves, the chronology was based entirely on stratigraphic and morphostratigraphic considerations and an attempt to fit the cave chronology in with regional geological and geomorphological history.

On these grounds I suggested that the palaeokarst might extend back in age to the Early Carboniferous Kanimblan Orogeny and that some cave filling, such as the caymanites, might be Latest Carboniferous in age, filling Carboniferous caves. Based on my previous work (Osborne, 1995), I suggested that the gravels on the surface at Jenolan and filling high-level caves such as Dreamtime Cave were most likely to be Permian in age. I recognized that the oldest phase of development of the currently open caves was *per-ascensum* development of the large cupolas such as the Temple of Baal ("3" in Figure 1A). I thought that this "phase 6" of cave development post-dated

Table 1. After Table 1 of Osborne (1999b)
A Framework Chronology for Jenolan Caves

Geological Era/Period	Phase	Event/Process	Feature	Example
Present	10	Stability	Low Mg Calcite Speleothems	Orient Cave
			Continued Weathering	Ribbon Cave
			Mg Rich Minerals	Ribbon Cave
Quaternary	9	Meteoric Speleogenesis 5 Exhumation	Nick Point Sediment Cliffs	The Ladder, River Cave
			Breakdown	Exhibition Chamber, Lucas Cave
A number of Cainozoic Phases	8	Meteoric Speleogenesis 4 Paragenesis	Conduits	The Slide, Lucas Cave
			Loops	Mons Meg, River Cave
? Tertiary	7	Meteoric Speleogenesis 3	Invasion Caves	Baal-River Passage
? Late Cretaceous	6A	Hydrothermal Speleogenesis 2 Hydrothermal Fills & Alteration	Crystal-lined Cavities	Mud Tunnels, River Cave
			Dolomitic crystal	Pool of Cerberus Cave
			Altered Algal Mats	Ribbon Cave
			Altered Palaeokarst	Olympia Steps, Ribbon Cave
			Non-Detrital Clay	River Lethe, River Cave
? Late Cretaceous	6	Hydrothermal Speleogenesis 2 Excavation	Cupolas	Persian Chamber, Orient Cave
			Halls	Jenolan Underground River
			Tubes	Ribbon Cave
Permian	5	Cave Fill & Landscape Burial	Fluvial Sediments	Dreamtime Cave
Permian	4	Meteoric Speleogenesis 2	Large Caves	Dreamtime Cave
? Early Permian	3	Hydrothermal Speleogenesis 1	Crystal-lined Cavities	Lucas Cave Entrance
? Latest Carboniferous	2	Marine Transgression and filling	Caymanites	Olympia Steps, Ribbon Cave
? Late Carboniferous	1	Meteoric Speleogenesis 1	Phreatic Caves	Olympia Steps, Ribbon Cave

deposition and partial removal of the Sydney Basin, suggesting that it was likely to be Cretaceous in age, resulting from hydrothermal activity related to the opening of the Tasman Sea and the uplift of the Eastern Highlands.

Just two years later, in March 2001, Horst Zwingmann produced the first K-Ar clay dates from Jenolan, and the whole world changed. Among the first dates to emerge was the Devonian date (389 Ma) for the sheared blue-grey clay from the Wilkinson Branch ("4" in Figure 1A). This made sense as a deformed palaeokarst deposit, correlated with the volcaniclastics, which disconformably overlie the limestone to the east, filling early caves.

The group of dates clustered around 340 Ma were, however, a great surprise and puzzle. There were no recorded Early Carboniferous strata within 180 km of Jenolan Caves, the nearest being in the New England Fold Belt (Figure 5), and it had never been suspected that palaeokarst, cave sediments or strata exposed or sitting on the surface in the Lachlan Fold Belt could be of this age. The real surprise from the K-Ar dating was that no Permian material other than overgrowth crystals were found in the caves and that surface

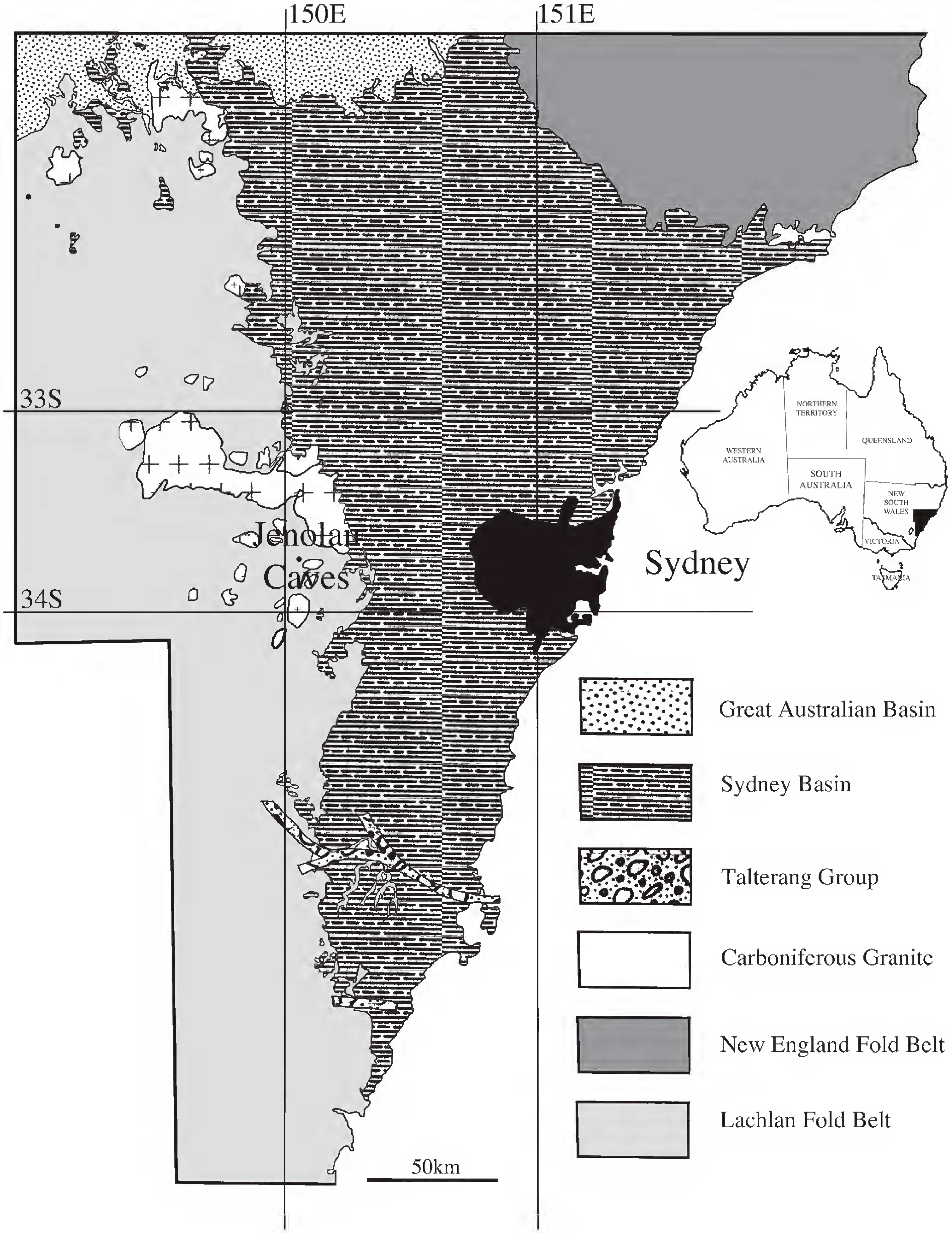

Figure 5, Regional geological setting showing location of Jenolan relative to Carboniferous strata.

deposits long thought to Permian, and represented on geological maps as Permian, such as those in the cutting on the Kanangra Wall Road at Mount Whiteley turned out to be Early Carboniferous.

A CURRENT SYNTHESIS

If we use the K-Ar dating of Osborne et al. (2006), recent observations in the caves and developments in thinking about landscape development in and near the Blue Mountains (e.g. van der Beek et al., 2001) to modify the Osborne (1999b) chronology we end up with Table 2 below.

Problems with the current synthesis

The lack of dating of events younger than the filling of cupolas by mass-flow deposits, except for the indication of burial under the Sydney Basin, makes the present synthesis quite limited. While there is good morphological evidence that cupola development and filling was followed by a major phase of paragenetic development there is no evidence yet as to whether this event pre-dated or post-dated deposition of the Sydney Basin, so I have represented this event twice in Table 2, below.

Present knowledge does not allow correlation between the cave record and the deposition of the Sydney Basin, one of the major events in the regional geological history. I, and many others, expected that due to the proximity of the caves to the edge of the Sydney Basin that basal Sydney Basin sediments would be found in the caves. It is possible that we do see the sediments in the form of the 303 Ma mass-flow deposits in the Temple of Baal.

WHERE NEXT?

Geological problems outside the caves

Studies in caves are frequently impacted by deficiencies in the basic knowledge of the geological and geomorphic environment in which the caves are located. There are several problems at Jenolan. While the structure and composition of the limestone is well known at a gross scale, more detailed structural, stratigraphic and sedimentological studies would help in understanding the factors influencing cave development.

Dating some key features of the local geology would also contribute to understanding the geological background to cave development. It has been generally assumed that the volcaniclastic rock overlying the limestone is similar in age to the Devonian Bindook Volcanic Complex, but this has never been confirmed by dating the volcanics at Jenolan. Similarly, a range of interpretations have been made about the age and origin of the andesite located directly to the west of the limestone near Caves House. These have ranged from an Ordovician or Silurian submarine lava flow to a Jurassic intrusion. Dating this rock would be of great assistance.

To the southwest the sequence at Jenolan is intruded by the Kanangra Granite and to the east by the un-named granite into which Hellgate Gorge is incised, both considered to be related to the Bathurst Batholith. Pogson and Watkins (1998) stated that the Kanangra Granite is likely to be middle Carboniferous (325-330 Ma) in age based on general dating of the Bathurst Batholith. They give the total age range for emplacement of the Batholith as being between 340 and 312 Ma. The dates for the emplacement of the Bathurst Granite overlap with those of the dated clays given by Osborne et al. (2006) making it likely the volcaniclastic source material for the clays came from volcanism related to the emplacement of the granite. As with the emplacement of the caymanites, this presents a palaeogeographic problem. How could the volcaniclastic debris enter the caves when at that time they should have been covered by kilometres thick of rock into which the granites intruded? Dating of the Kanangra Granite and un-named granite may help resolve this problem.

General problems in the caves

1. Underground cave/geology relationships

Apart from some honours thesis work by McClean (1983) and Allan (1986) and some small scale localized work by David Colchester and me, there has been practically no mapping of either the bedrock and/or of the karst geology in the caves. One factor preventing this was a lack of cave maps of suitable quality and resolution onto which field observations could be plotted. The recent completion of the work of the Jenolan Survey Project means that high resolution plans and sections are now available for the whole of the show cave system.

Mapping the bedrock and karst geology of the caves will make explicit relationships between cave development bedrock lithology and geological structures in the bedrock. It will also show the distribution of palaeokarst features in the bedrock, sediments filling the caves and the relationship between speleothems, mineral deposits and bedrock substrate. Unlike conventional cave maps, this type of mapping will indicate were the cave wall is composed of bedrock and where it is sediment, indicating the outlines of sediment-filled cavities.

Table 2. A Revised Jenolan Chronology

Relative	Ma	CAVE EVENT	CAVE EXAMPLES	BEDROCK/SURFACE
Tertiary-Recent		Continuing fluvial action and removal of old fills Breakdown	Queens Canopy Exhibition Chamber	Present surface streams
Early Tertiary		Active Streamways Generation 6 Caves	Imperial Streamway Lethe	Erosion 6 Extra Uplift of Blue Mts. Inner valley?
		Invasion meteoric caves Generation 5 Caves	Baal-River Tunnel	Stripping of Sydney Basin
				Erosion 5
Mid Cretaceous	100?			Uplift of E Highlands
		Lacustrine & Calcite Raft Deposits	Imperial	
		? Paragenesis Generation 4 Caves	Mons Meg, Pool of Reflections, Slide	
Permian-Mid Triassic	258-240	Secondary Illite Growth	Selina & Baal	Sydney Basin Cover
Latest Carb - Triassic				Sydney Basin Deposition
L Carb-Permian		? Paragenesis Generation 4 Caves	Mons Meg, Pool of Reflections, Slide	
Late Carboniferous	303	Mass-flow sediments with brown matrix	Baal, Orient, Imperial	Erosion 4
	340-312			Post-Tectonic Granites
Mid Carboniferous	320-327	Mass-Flow sediments with yellow matrix		Erosion 3, Kanangra Rd & Old School Diamictite
E Carboniferous	340	White & Yellow Clay	Baal, Orient, River	Volcanism
E Carboniferous		Per Ascensum 1 Generation 3 Caves	Baal, Orient, Pool of Cerberus	Erosion 3
E Carboniferous	>340	Crystal vughs	River, Imperial	
E Carboniferous	>340	Caymanites fill Generation 2 Caves	River, Grand Arch DCH	? Marine Transgression
		Generation 2 Caves		
			? Crackle Breccias	
E Carboniferous				Kanimblan Folding
Late Devonian		Unlikely to be found at Jenolan		Lambie Group
		Unlikely to be found at Jenolan		Erosion 2
		Unlikely to be found at Jenolan		Tabberabberan Folding
Late Early Devonian				Volcanics overlying the Jenolan Caves Limestone
Devonian	389	Blue clay palaeokarst	Wilkinson Branch	
	>389	Generation 1 Caves		Erosion 1
Latest Silurian				Jenolan Caves Limestone

While it is easy to see the benefits of such an undertaking for cave management, interpretation and science this project would require a considerable amount of time and would require fieldwork by experienced workers with eyes for carbonate geology, structural geology, palaeokarst, cave sediments, speleothem and cave minerals, hopefully working in the field together, along with significant funds allocated for lab work in petrology, structural geology, x-ray mineralogy, sedimentology etc.

2. Age and origin of the crackle breccias

Crackle breccias consist of bedrock fragments in a crystalline matrix. They are usually grain-supported and often have the appearance of adjacent blocks that have been pushed apart by the emplacement of the matrix, and fit together like pieces of a jigsaw puzzle.

There are two large exposures of crackle breccia in the Jenolan Show Caves, both difficult to access and sample. One forms the ceiling of Katie's Bower in the Chifley Cave ("5" in Figure 1A) while the other is exposed in the cave wall and ceiling at the bottom of the Slide in Lucas Cave at its junction with Exhibition Chamber ("6" in Figure 1A). The Katie's Bower exposure (Figure 6A) shows evidence of rotated blocks while the Lucas Cave exposure (Figure 6B) shows large angular blocks. Crackle breccias are also found at Wombeyan Caves (Osborne, 2004) and Bungonia Caves.

There are conflicting views about the origin of this type of breccia. Polish economic geologists have attributed the origin of these structures in dolomite to solution-collapse following the removal of underlying limestone (Sass-Gustkiewicz, 1974) while American petroleum geologists (Loucks, 2007) have attributed them to the collapse of cave systems due to burial by an overwhelming mass of overburden. The latter explanation seems most likely in eastern Australia.

While the Limestone was probably not covered by a great thickness of Sydney Basin sediments, by the end of the Devonian it was probably buried by a significant thickness of mid-Devonian volcaniclastics and siliceous late Devonian Lambie Group sediments. While at present there is no direct evidence for the age of these breccias, it seems likely that they are of significant, possibly Devonian, age.

3. Age of the caymanites

Unconformable caymanites (marine carbonate turbidite palaeokarst, Jones, 1992) are exposed in NSW in caves and in surface outcrop at Jenolan, Bungonia and Borenore and in caves at Colong and Wellington. While stratigraphic relationships suggest they predate the Early Carboniferous clays at Jenolan, they contain no datable macrofossils and attempts to date them using microfossils have proved unsuccessful as none were recovered. Palaeomagnetic dating has been attempted with little success except to indicate that they most likely predate the Sydney Basin.

Caymanite deposits are common at Jenolan in the show caves, in the open arches, in the wild caves and in surface exposure. One of the most important exposures is at Olympia Steps in the Mud Tunnels section of River Cave ("3" in Figure 1B, Figure 6C). Here an incomplete section more than 5 m thick is exposed with a clearly defined unconformable upper boundary, representing the palaeo-cave ceiling (Figure 6D). The caymanite deposits include a range of lithologies including beds of coarse crinoidal grainstone (Figure 6E), graded-bedded sequences (Figure 6F) and fine, cryptocrystalline mudstones.

The caymanites appear to represent an Early Carboniferous marine transgression over parts of the Lachlan Fold Belt, which is not recorded in the conventional stratigraphic record. It is very difficult to conceive an Early Carboniferous palaeogeography that would allow marine water and sediment to enter caves in the limestone at this time. The palaeogeography of Late Carboniferous to Early Permian times, however, is much more conducive to such an event. So I (Osborne, 1999b) concluded that the caymanites were likely to be Late Carboniferous to Early Permian (Table 1). The problem is that crosscutting relationships observed in the caves by Osborne et al. (2006) and other examples seen since all suggest that the caymanite is older than the dated Early Carboniferous clays. Field evidence also suggests that the caymanite is older that the crystal filled vughs, which are also older than the dated Early Carboniferous clays. Osborne (2007) discussed the palaeogeographic problems arising from the emplacement and survival of Early Carboniferous sediments at Jenolan as part of the general problem of explaining why ancient caves should survive at all and suggested differential vertical movements of fault blocks as a possible solution.

A new attempt at palaeomagnetic dating of the Jenolan and other caymanites in New South Wales and further studies of their stable isotope geochemistry is planned and may help to resolve this problem. Finding datable fossils or microfossils in the caymanites would be the best outcome, but that seems unlikely.

4. Effect of granite emplacement on the caves

While I have put a lot of thought into the palaeogeographic implications of emplacement and later un-roofing of the Carboniferous post-tectonic granites for the survival of Early Carboniferous caves at Jenolan, it was not until Dr Percival raised the issue of "How did the granites affect the caves?" in his presentation at the Jenolan Symposium that I thought about whether I had seen any evidence that the caves were affected by the emplacement of the granites.

Given that the boundary of the un-named granite into which Hellgate Gorge is incised is 2 km east from Jenolan Caves, and that the emplacement of this granite was likely to have occurred between 325-330 Ma, one might expect to see an impact on caves older than 340 Ma and on the 340 Ma sediments in these old caves. The emplacement of granites is

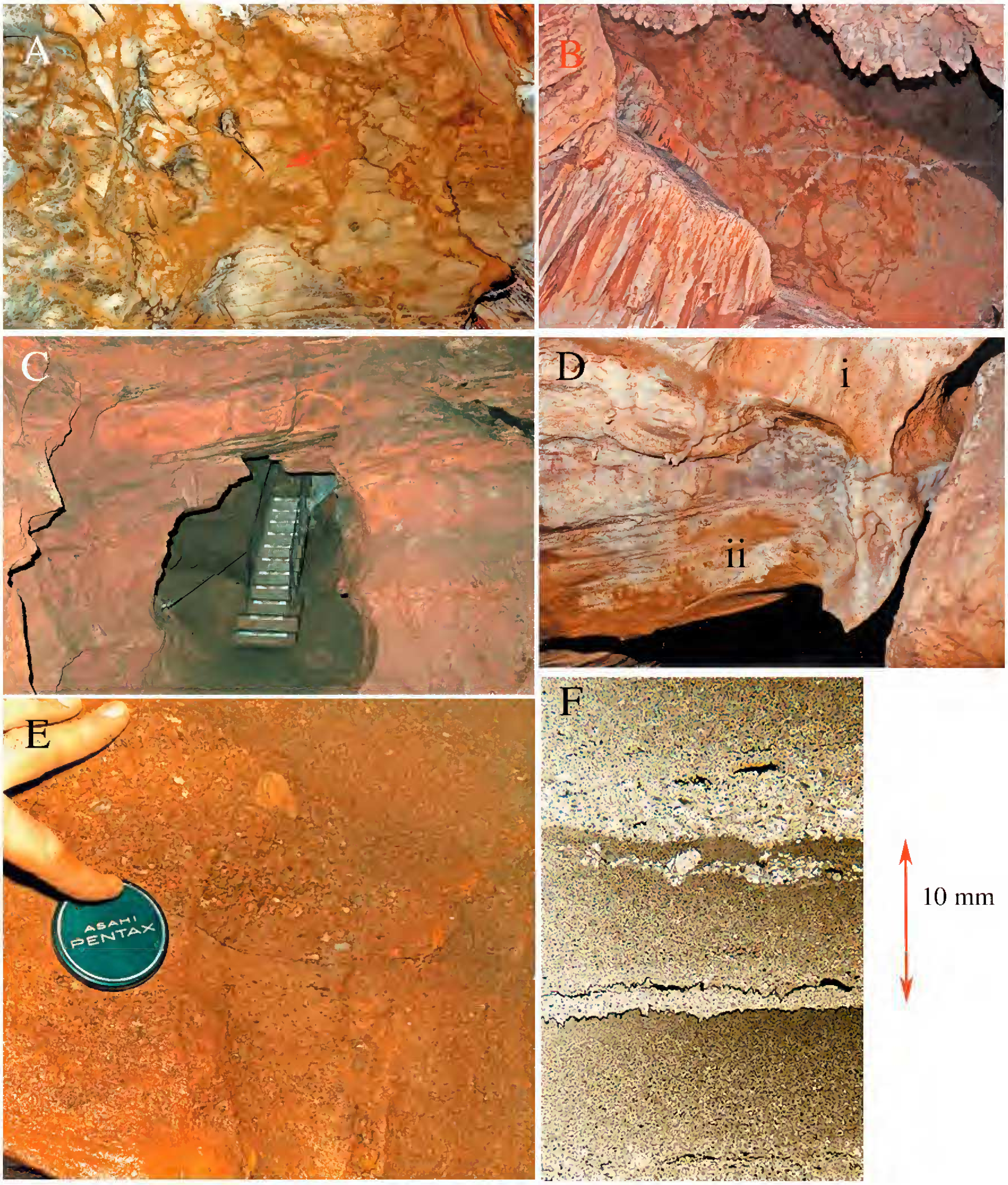

Figure 6, Crackle breccia and caymanite. (A) Crackle breccia in Katie's Bower ceiling, note rotated block in centre of image indicated by red arrow; (B) Crackle breccia exposed a western wall and ceiling near junction of The Slide with Exhibition Chamber. Image courtesy Ted Matthews; (C) Olympia Stairs caymanite exposure, looking south at "3" in Figure 1B; (D) Upper boundary of caymanite deposit representing ceiling of filled palaeocave in the Mud Tunnels near Orient Stairs ("4" in Figure 1B) i = dipping Jenolan Caves Limestone bedrock, ii = sub-horizontally dipping caymanite; (E) Exposure of coarse crinoidal grainstone facies caymanite in Barrelong Cave, Lens cap 55mm; (F) Thin section of laminated and graded-bedded caymanite from Olympia Stairs deposit.

usually accompanied by significant heating of the surrounding country rock, resulting in contact metamorphism. In the case of the 340 Ma illite-bearing clays one might expect this to result in the growth of fine-grained spiky illite crystals during the peak phase of granite emplacement between 325-330 Ma. We do find secondary spiky illite crystals on clays from the Temple of Baal and on clays filling a crystal vugh in Imperial Cave, but these give dates between 258-240 Ma, more likely to be related to burial under the Sydney Basin than to the emplacement of the granites.

Heating by batholiths often leads to hydrothermal mineralization, and close to large bodies of limestone could lead to hydrothermal cave formation and/or the formation of crystal veins and vughs. Once again all the available evidence suggests that the large *per-ascensum* cupolas and the crystal vughs, both of which could be hydrothermal in origin, are older than the emplacement of the granite.

While the 12 km distance from the Kanangra Granite might rule out any great impact from it, one might expect an effect from the nearby un-named granite in which Hellgate Gorge is incised. One possible explanation for the apparent lack of impact by granite emplacement on the caves could be that the un-named granite is significantly older than 325-330 Ma. If the un-named granite was emplaced before 340 Ma, its emplacement could have been responsible for both hypogene cave and crystal vugh development without having any impact on the dated clays. This idea could and should be tested by dating the un-named granite.

A more radical possibility is that the rock mass containing Jenolan Caves was not in its present position relative to the granites at the time of their emplacement, but was "shuffled" into its present place by fault movements after the emplacement of the granites but before the deposition of the Sydney Basin. This is not completely impossible as there is some evidence that the western boundary of the limestone is faulted and House (1988) suggested movement of the major north-south trending fault to the east of the limestone post-dated emplacement of the un-named granite. The relationship between the caves and the granites remains a puzzle and work and thought needs to be applied to solving this problem.

5. Age of gravels and mass-flow deposits

Dating by Osborne et al. (2006) gave two different ages for the polymictic, matrix supported, cobbly gravels at Jenolan Caves; approximately 320-327 Ma for deposits on the Kanangra Walls Road (Figure 7A) and at the old school and 303 Ma for the deposit that appears to have once filled much of the Temple of Baal (Figure 7B).

Without the benefit of dating, Osborne (1995), recognised that there were two distinct groups of cemented gravels at Jenolan; polymictic gravels with pyrite such as those in Dreamtime Cave (Figure 7C) and polymictic gravels without pyrite. It was suggested that those with pyrite in their cement were not Cainozoic in age and were most likely latest Carboniferous to earliest Permian in age. None of these gravels have yet been dated and their relationship with either group of dated Carboniferous mass-flow deposits at Jenolan or with other undated gravels is not at all clear.

It is very likely that some gravel deposits result from the re-working of older deposits. Some deposits now on the surface may not be surficial deposits at all, but deposits filling unroofed caves, such as the gravel deposit on top of the Grand Archway (Figure 7D). A great deal of fieldwork in very steep country, as well as in the caves, is required if any progress in understanding the age and relationships of the gravels is to be made.

6. Dolomite and ankerite

The Jenolan Caves Limestone is very pure and in bulk contains very little magnesium. The caves, however, contain significant isolated occurrences of aragonite speleothems, often associated with deposits of magnesium-bearing minerals such as hydromagnesite and huntite and at one locality dolomite is actively being deposited.

Ankerite veins protrude from the cave walls in close proximity to aragonite deposits in Ribbon Cave ("8" in Figure 1A), Jubilee Cave ("9" in Figure 1A) and in the Mud Tunnels. Figure 8A shows protruding ankerite veins at the southern end of Ribbon Cave associate with a brown fill or alteration zone that has yet to be sampled or investigated in detail. Also growing from an apparently dolomitic substrate in Ribbon Cave is a spectacular aragonite speleothem mass called the Lyrebirds Nest (Figure 8B) with spiral vermiform aragonite helictites tipped with growing cauliflower-shaped masses of moist huntite with a texture like cream cheese.

Some of the most impressive and extensive aragonite speleothems occur in Pool of Cerberus Cave ("10" in Figure 1A) associated with ferruginous mud and soggy yellow weathered dolomitic limestone. One section of the cave path has been cut through some of the substrate to reveal yellow dolostone with angular ferruginous fragments (Figure 8C). Some of the aragonite speleothems in Pool of Cerberus Cave and their rusty clay substrate are shown in Figure 8D.

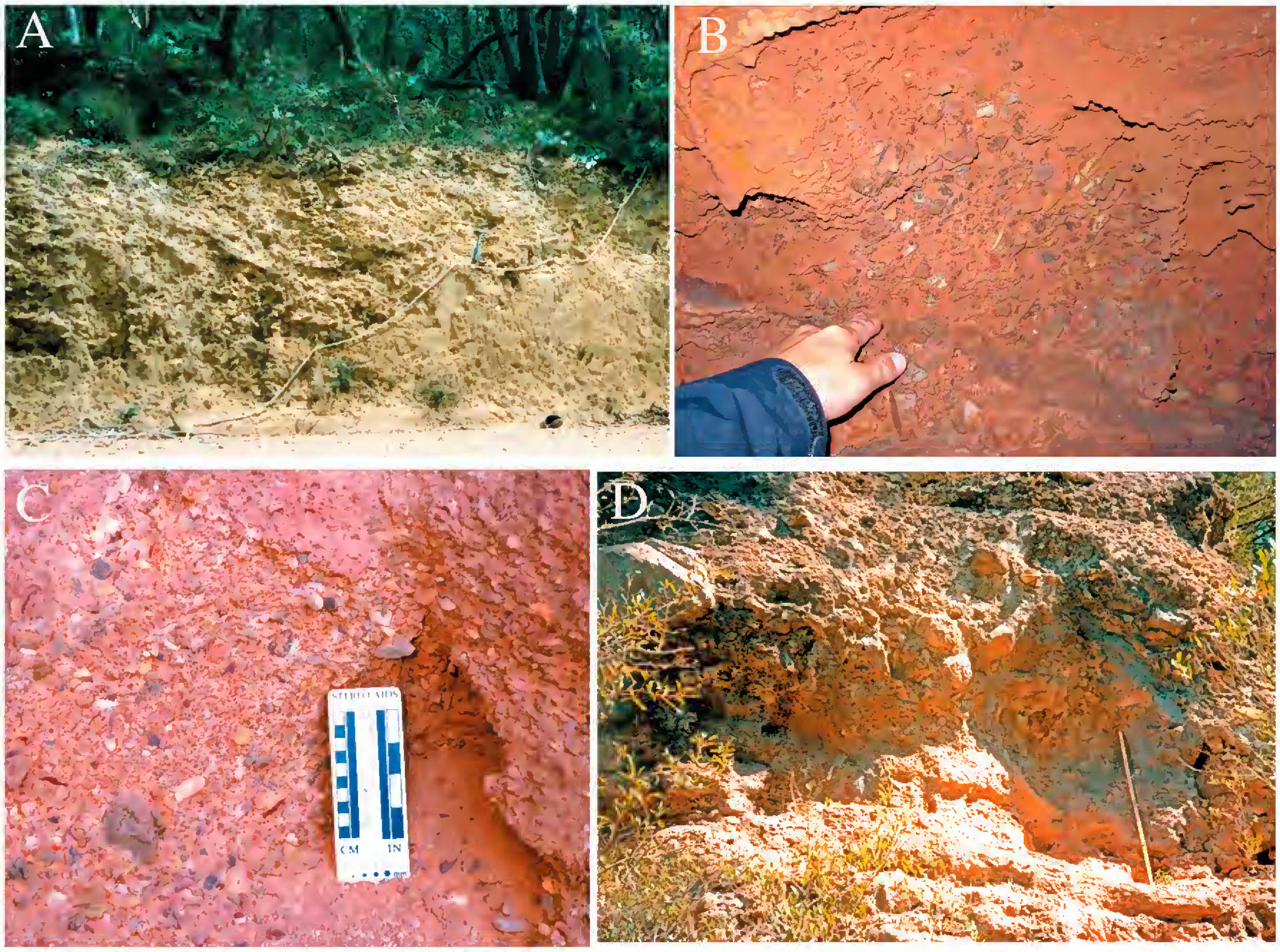

Figure 7, Gravel deposits. (A) Kanangra Road, tape marks unconformity at base of gravel deposit; (B) Mass-flow deposit in western side of the Temple of Baal, Image courtesy Bojan Otoničar; (C) Cemented gravel in Dreamtime Cave; (D) Gravel deposit, possible unroofed cave in saddle above the Grand Archway.

The scattered deposits of aragonite and magnesium minerals appear to be closely related to ankerite veins and irregular dolomitic bodies in the limestone. Some of the caymanite deposits are dolomitized and it appears that a single bed towards the top of the limestone sequence has been extensively dolomitized. Weathered dolomitic/ankeritic net veins can be observed in surface limestone outcrops. One example is the veins exposed in the bank of the drain running in front of the entrance to Binoomea Cut ("7" in Figure 1A, Figure 8E).

Contact Cave, located high on the eastern side of McKeown Creek valley, is named because it was thought to have formed at the boundary between the Limestone and the overlying Devonian volcanics. The cave is close to, but not on the boundary and the rock forming the eastern wall of the cave and much of the ceiling is not composed of volcaniclastics but of rusty yellow weathering dolomitic limestone. Complex aragonite anthodites, with dolomite crystals forming at their tips, grow from the weathering dolomite substrate (Figure 8F).

Rowling (2004) described aragonite deposits in several caves at Jenolan and suggested a relationship with magnesium, strontium and sulfate ions, all of which could be sourced from pyritic dolomite and ankerite. Ross Pogson, David Colchester and I have made some investigation of the ankerite and dolomite veins and outcrops in the caves, but much more needs to be done and funding is required for chemical and isotopic analyses.

7. "Yellow stuff"

Visitors and cave guides often inquire and sometimes argue about the nature of striking yellow coloured deposits partially filling or intersected by the caves. These occur throughout the caves, but are mostly noticed in the southern show caves. Now that new maps are available it would be useful from both a scientific and an interpretation point of view to map and identify these deposits. Where these deposits have been investigated the "yellow stuff" turns out to encompass a range of materials with a similar colour and often a gooey texture. These include 340 Ma

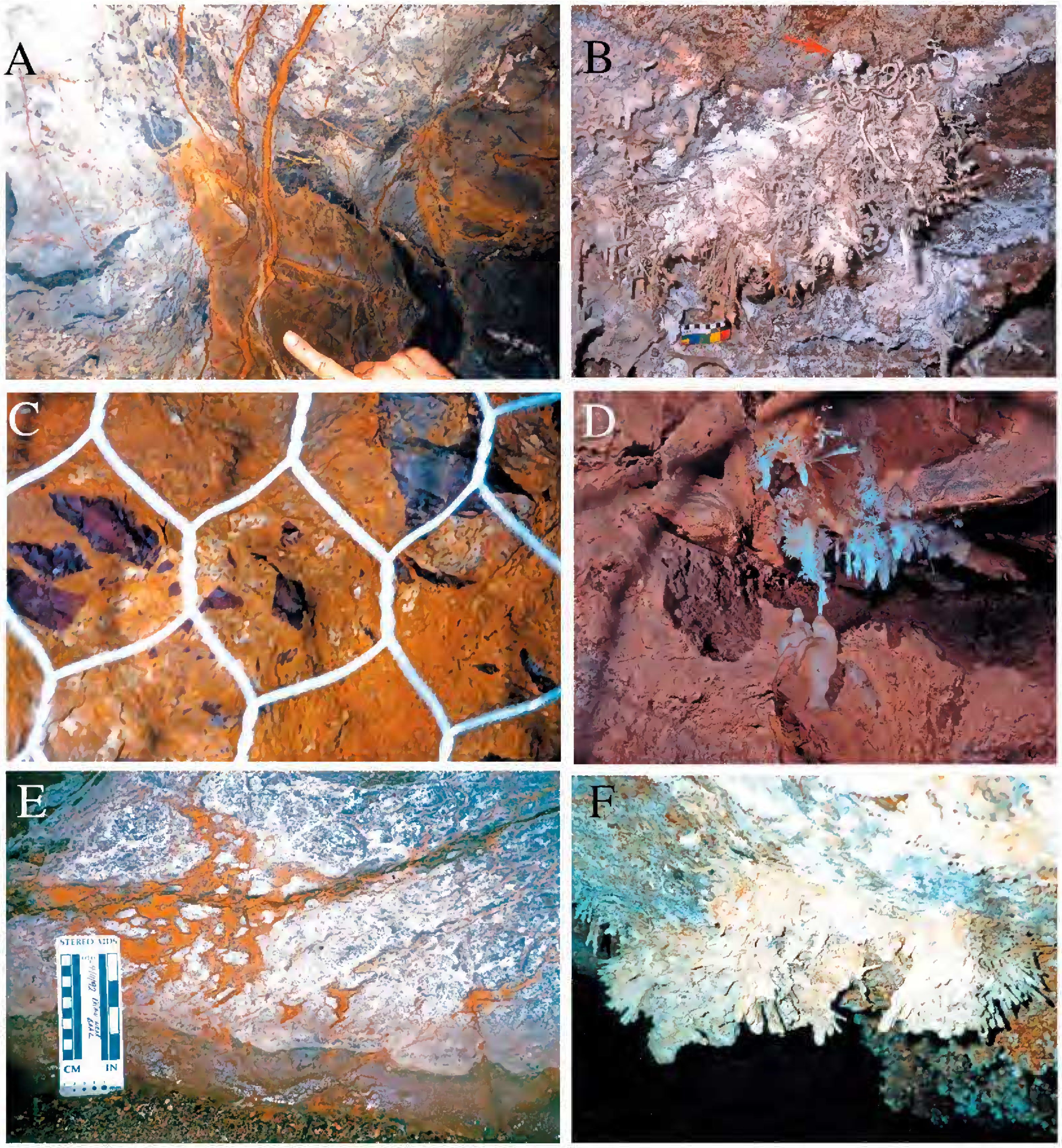

Figure 8, Dolomite and ankerite. (A) Protruding orange ankerite veins and undetermined brown material on wall of Ribbon Cave ("8" in Figure 1A); (B) The Lyrebird, Ribbon Cave, a complex aragonite speleothem mass with soft cauliflower-like deposits of huntite (indicated by red arrow) growing on the tips of vermiform helictites. Black squares on scale 10mm; (C) Tan dolomitic mass with ferruginous clasts intersected in excavated ceiling of Pool of Cerberus Cave ("10" in Figure 1A) adjacent to significant deposit of aragonite speleothems; (D) Aragonite stalactites growing from ferruginous mud with curved laminations (possibly weathered dolomite) in close proximity to "C"; (E) Dolomitic net veins in limestone bedrock exposed in side of drain adjacent to entrance to Binoomea Cut ("7" in Figure 1A); (F) Aragonite speleothems (anthodites) with dolomite crystals being actively deposited at their tips, Contact Cave.

clays, weathered ankerite veins, altered algal mats and dolomitized diagenetic infill sediments with bedrock fossils.

Figure 9 shows some examples of "yellow stuff" from the southern show caves. Figure 9A is one of several crumbly sandy pendants that hang from the ceiling of Pool of Cerberus Cave. This material is clayey sand with no carbonate content and contains small double-terminated quartz crystals, so it could be Early Carboniferous volcaniclastic sediment. Figure 9B is either a limestone boulder or a bedrock projection from the cave wall exposed in the side of a cutting in an old tourist path south of Olympia ("5" in Figure 1B). The rock has a thin coating of yellow

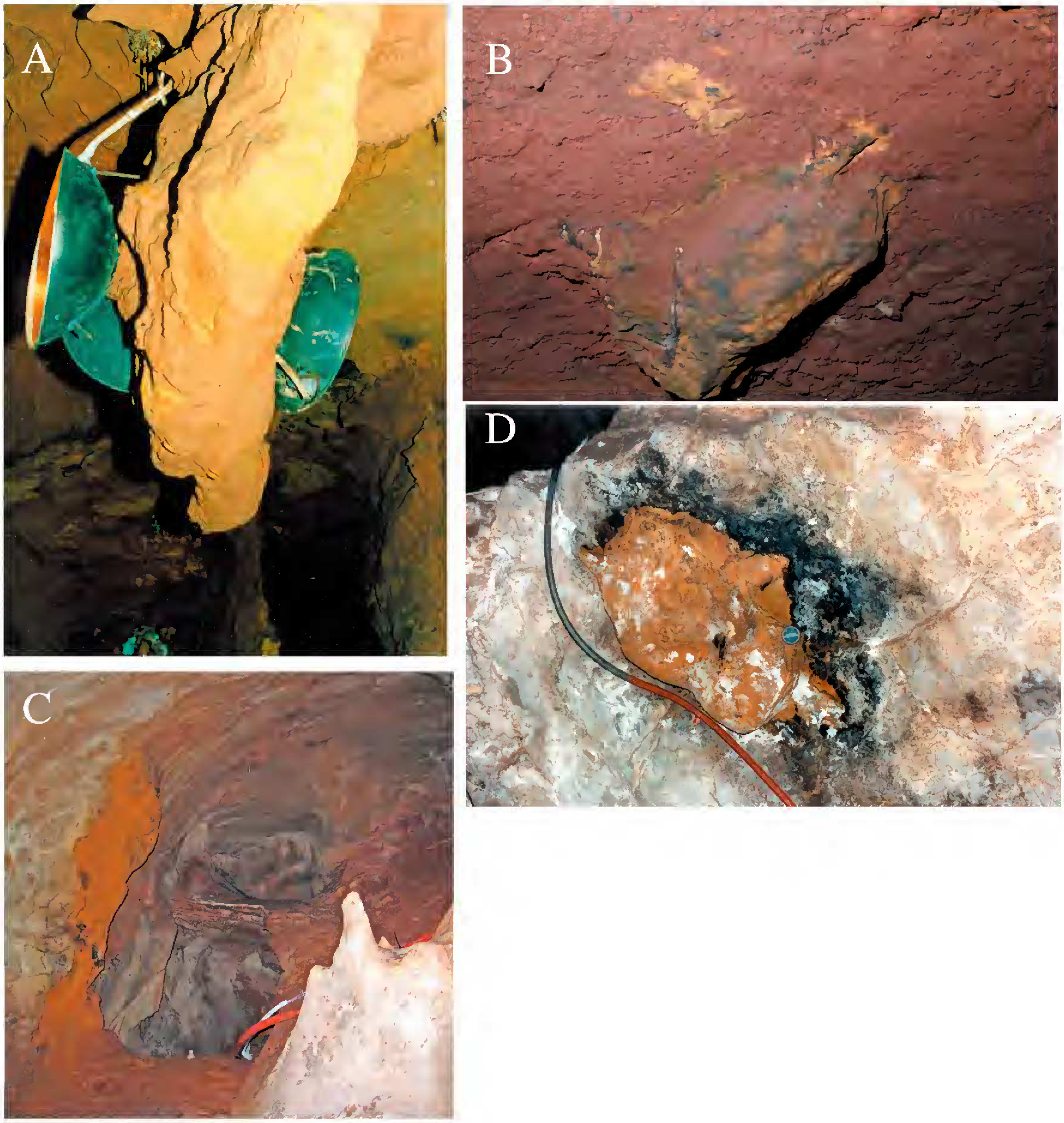

Figure 9, Yellow stuff. (A) Ceiling pendant of siliceous "yellow stuff" with old light fittings attached in Pool of Cerberus Cave; (B) Undetermined yellow coating on exhumed boulder or cave wall in cutting of old tourist path south of Olympia ("5" in Figure 1B); (C) Dated Early Carboniferous volcaniclastic sediment (orange) at T-junction in River Cave ("6" in Figure 1B) Image courtesy Bojan Otoničar; (D) Leisegang-banded ironstone with quartz grains, separated from bedrock by manganiferous reaction rim on wall of the Cathedral, Lucas Cave ("11 in Figure 1A).

paste, which has yet to be analysed. Figure 9C shows a bright orange remnant of dated Early Carboniferous clay located at the "T" junction in River Cave ("6" in Figure 1B). Figure 9D shows a yellow ferruginous remnant, consisting of a small number of quartz grains in a ferruginous matrix, separated from the bedrock by a layer (? reaction rim) of manganiferous paste on the wall of the Cathedral, Lucas Cave ("11" in Figure 1A). The origin and previous extent of this deposit is unknown.

While in most cases the yellow colouring is likely to be ferruginous, Ian Cooper pers. comm. (2013) has reported observing native sulfur in both River and Jubilee Caves, however this has yet to be confirmed by sampling and analysis. Now that good maps are available, a collaborative effort between cave guides, marking localities of “yellow stuff” on maps and researchers sampling and characterising the material is possible and could result in both better interpretation and enhanced scientific understanding.

Southern show caves

The most important step in understanding the history of the southern show caves is dating the paragenetic sediments. These deposits are of two types, sequences in wall niches and thick deposits either filling passages or protected by flowstone caps. The later type appear to be remnants of sediment that probably once filled the whole length of these conduits, exposed at the present erosion head.

Wall niche deposits are easily observed on the niches in the walls of River Cave north of the Pool of Reflections (“2” in Figure 1B, Figure 10A). Sections exposing sediments at erosion heads also occur in River Cave. Sections are exposed at either end of the Mons Meg paragenetic loop. An 8-metre section of fine laminated mud (Figure 10B) fills what appears to be the ancient northern route of River Cave before its down-dip migration to the west (“7” in Figure 1B) while a section more than 6-metres high is exposed at the Ladder at the southern end of the Mons Meg Loop (“8” in Fig 1B, Figure 10C). Another 8-metre section is exposed at the northern end of the Mud Tunnels near Mossy Rock (“9” in Figure 1B, Figure 10D).

Northern show caves

Much of my work has focused on the southern show caves as it is easier to study the cupolas and observe morphostratigraphic relationships between features produced by different phases of cave development there. I had assumed, falsely as it has turned out, that the northern show caves were essentially stacked levels of former underground streamways, filled with fluvial sediment, representing a series of underground captures of McKeown Creek (Osborne, 1999b).

What I have since realised about the northern show caves is the difference in morphology between the cavities along which the main tourist paths run in Imperial Cave, Jubilee Cave and most of Chifley Cave and the morphology of the cavity at river level in the Imperial Streamway.

Near the main tourist paths the cave walls are white and smooth. Scallops are rare and there is little sign of sand (Figure 11A). Cave morphology is suggestive of excavation by paragenetic rather than fluvial processes. Below, in the streamway, the walls and projections from the ceiling appear to be made of fresh limestone and are covered with many small scallops, indicating fast-flowing water (Figure 11B). In addition to the scallops, the rock surface is rough due to the presence of small sharp pieces of insoluble material projecting from the rock surface indicating that the water in the stream is unable to dissolve small pieces of chert and silicified fossils in the limestone. There is clean sand with ripples in the streambed and there are some overbank deposits of mud formed during flood events. The active processes we see today in the Imperial Streamway are clearly not the key to the past as seen in the higher-level passages.

Recent casual observations have shown that while there are relatively uncommon deposits of fluvial sand and gravel, the principal sediment types in the northern show caves are crystal rafts (Figure 12A), muds (Figure 12B) and poorly-sorted mass-flow deposits (Figure 12C), indicative of lacustrine or paragenetic conditions rather than fluvial.

While significant progress has been made in unravelling the developmental history of the southern show caves, there has been less progress in the north and much remains to be done. There is a least one PhD project in sorting out the sediments and morphology in the northern show caves.

TAKING THE NEXT STEPS

Despite their ease of access the Jenolan Show Caves are among the most complex and confusing caves to study and understand. There are, however very good reasons not just to persist with research at Jenolan but to expand it. These include the scientific significance of the caves, the significance of the caves for interpretation and education, the significance of the science for the conservation, management and sustainable development of the caves, and their natural heritage significance, which I believe could be demonstrated to be at a level appropriate for nomination to the World Heritage List.

Scientific significance

Jenolan Caves are among the world’s oldest and most complex limestone caves containing unconsolidated sediments dating back to the Early Carboniferous and preserving records of past events not found elsewhere. The caves are important in illustrating the effects of multiple phases of different cave forming mechanisms, *per-ascensum,* paragenetic, fluvial and breakdown being overprinted within a small body of limestone.

The caves are also important for their great diversity of mineral species and for the particular

Figure 10, Paragenetic Sediments.
(A) Mud deposits on niches in eastern wall of River Cave, north of Pool of Reflections ("2" in Figure 1B) wall approx. 6 m high;
(B) North extension of Mons Meg section 8 m + ("7" in Figure 1B);
(C) Section at Ladder 6 m+ ("8" in Figure 1B);
(D) Section at Mossy Rock 8 m thick below flowstone ("9" in Figure 1B)

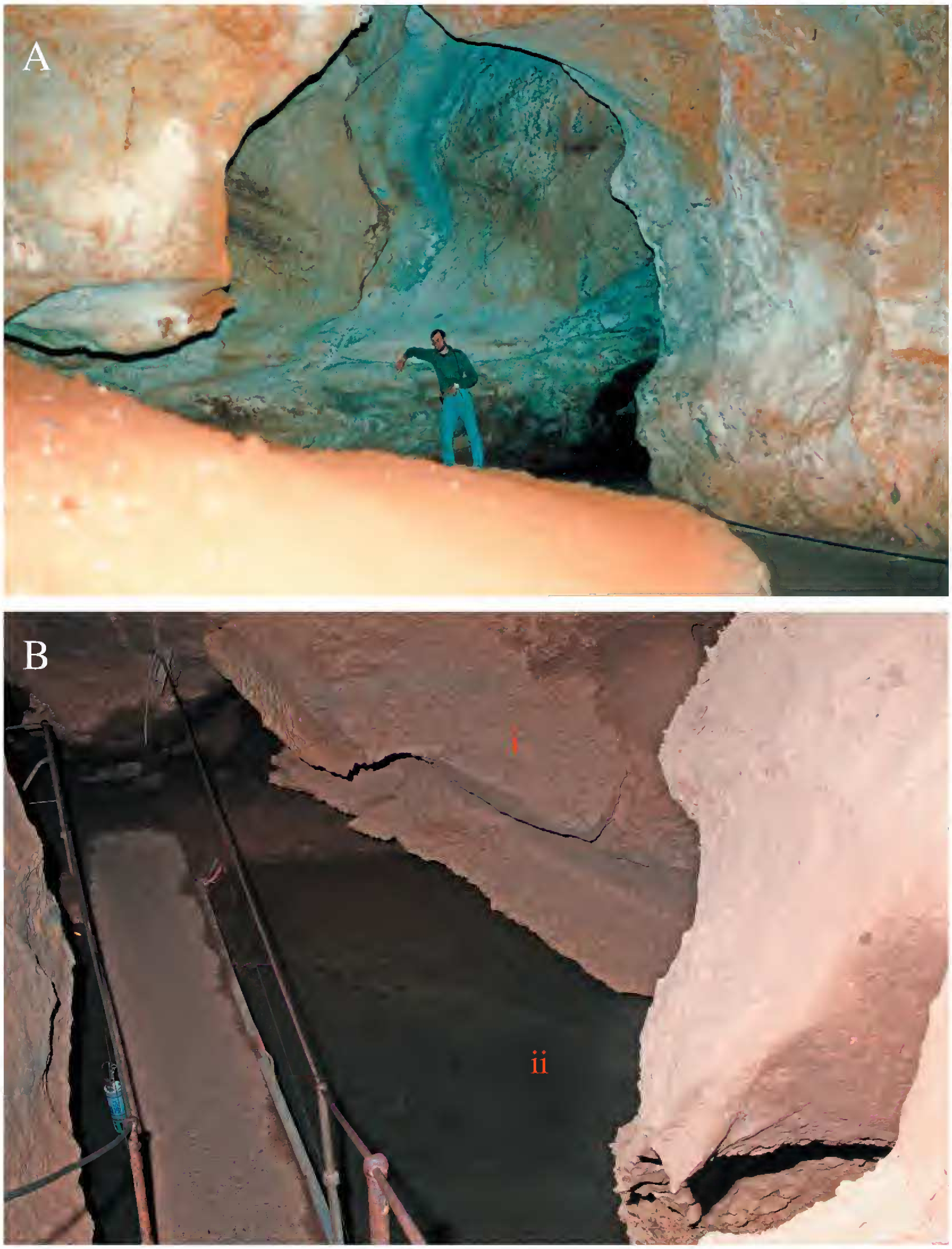

Figure 11, Morphology of cave at tourist path level compared with that at stream level in Northern Show Caves. (A) Imperial Cave tourist path, looking north, north of the Bone Box ("12" in Figure 1A). Note relatively smooth walls and lack of scallops; (B) Looking down to the Imperial Streamway ("13" in Figure 1A) note scallops on ceiling at "i" and ripples in sand in streambed at "ii".

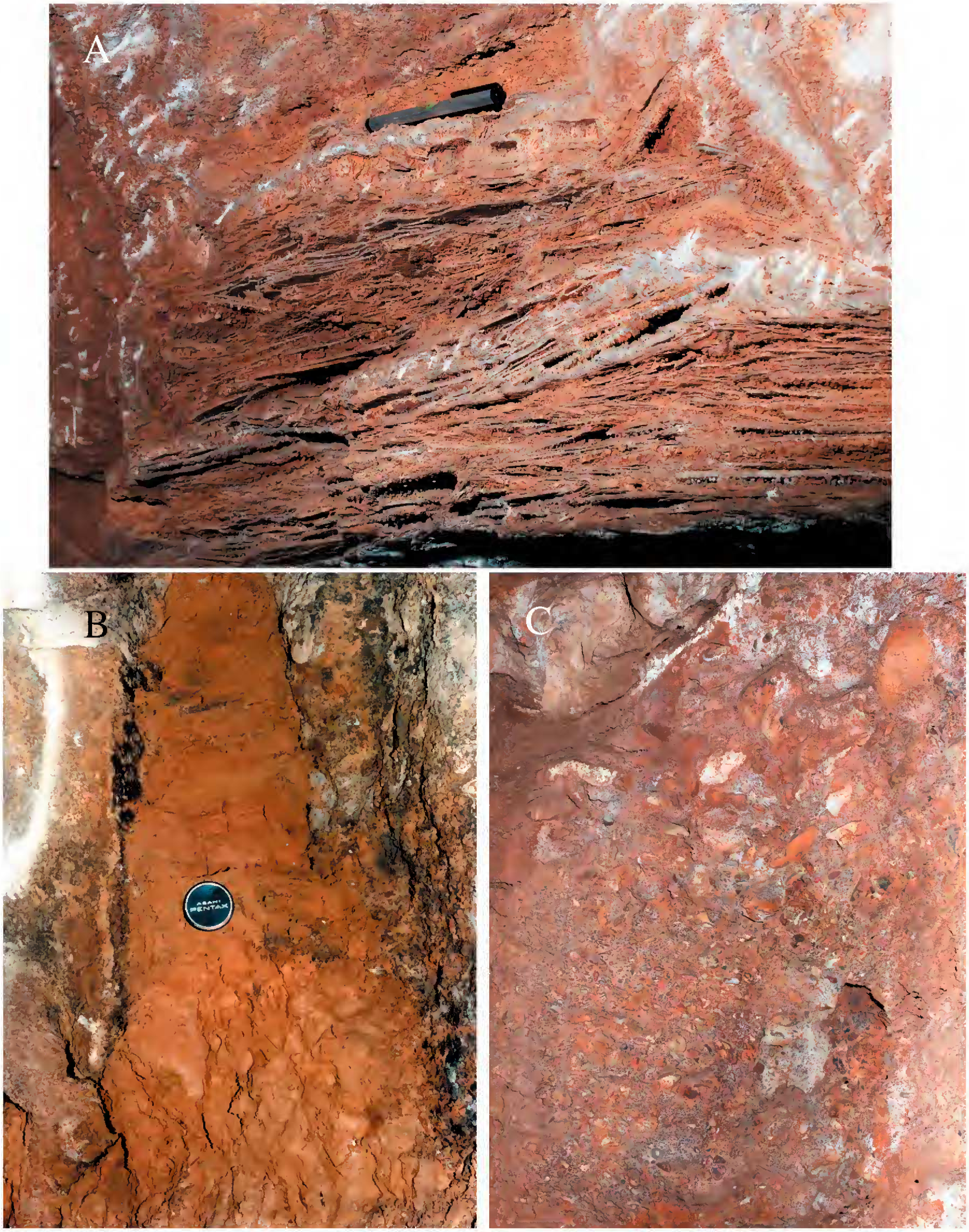

Figure 12, Sediments in Northern Show Caves. (A)Calcite raft deposit in eastern wall of excavated tourist path in Imperial Cave ("14" in Figure 1A). Pocket spirit level is 80 mm long; (B) Laminated mud deposit near the mystery, Katie's Bower, Chifley Cave ("15" in Figure 1A). Lens cap 55 mm; (C) Mass flow deposit of cobbles and gravel in a mud matrix exposed in cutting of path to the Imperial Streamway ("13" in Figure 1A).

expression of some forms of speleothem (see Pogson et al. this volume).

Significance for interpretation and education

As Australia's most visited show caves, with some 240,000 cave visits annually, Jenolan Caves are an important site for scientific and environmental interpretation to the public, particularly for the interpretation of Earth sciences. Of these visits, 11,700 annually are by primary and secondary students, making it one of the State's most important school excursion venues.

Good interpretation requires a good story, derived from rigorous theory, synthesis and a strong factual base. For the caves at Jenolan we have a beginning in the Early Carboniferous and an end in the present cave environment; we know some of the events in between, but not their sequence. Theory and synthesis are now beginning to emerge, but as illustrated in the case of "yellow stuff" many obvious features of the caves have not yet received serious scientific attention and cannot be properly interpreted to the public.

Significance for conservation, management and sustainable development

In order to properly conserve, manage and develop a natural heritage site it is essential to know what is there and if it is highly significant, rare, fragile or vulnerable. Inventory studies did not exist when Jenolan Caves were first developed for tourist use in the late 19th and early 20th centuries, so our lack of good data to inform conservation, management, development and interpretation is partly historical, but like most major show caves world-wide there has never been an inventory study of the show caves at Jenolan. Without an inventory study, monitoring of caves is deficient (Osborne, 2002) so an inventory study should be undertaken before any major changes in cave management occur.

The work of Osborne et al. (2006), and the continuing research proposed here has a focus on unconsolidated sediments and less attractive mineral deposits: materials that often receive less care and regard during cave maintenance and when development is proposed. Remnant sediment masses, such as those near the Pool of Reflections could easily be destroyed by over zealous use of high-pressure water cleaning, while the first dated Early Carboniferous clay locality was formerly used as a source of material to repair drain pipes.

These ancient materials have, however proved to be essential for understanding the history of cave development and are records of past events not previously known to science. The present risk at Jenolan as in most other show caves is that something of great significance might be harmed or destroyed simply because it is un-recognised and un-recorded.

World Heritage significance

While Jenolan Caves are within the Greater Blue Mountains World Heritage Area (GBMWHA), neither Jenolan Caves, nor any of the other landscape and geological features of the GBMWHA were among the reasons for listing. There are many cave and karst areas now included on the World Heritage List so adding more would present a challenge. However, there has been interest over many years in the possibility of including Jenolan as part of an Eastern Australian Impounded Karsts nomination or in making a case to have the values at Jenolan Caves included in the existing GBMWHA listing.

World Heritage listing requires places to be of "outstanding universal value" and for non-living natural places a detailed comparison of significance with places having similar values internationally is required. It is difficult to find caves internationally with which to compare Jenolan, but I think there are some caves in central Europe with which this may be possible. A detailed understanding, listing and evaluation of the values, and an inventory study would be required. Any action on World Heritage listing is a considerable undertaking and successful nominations internationally always require the mobilization of government and academic scientific resources.

CONCLUSIONS

There are clear steps to be taken to further our understanding of the origin and evolution of Jenolan Caves. Taking these steps is not only of scientific importance, but will greatly enhance the conservation, management and interpretation of Australia's most significant tourist cave system and is also essential for progress towards World Heritage listing of Jenolan Caves. The next steps require an application of cave science at a scale not previously seen in Australia. Are we up to the challenge?

ACKNOWLEDGEMENTS

This paper is an expanded version of a paper presented at *The Science of Jenolan Caves Symposium* held at Jenolan Caves on May 23-24, 2013. For the author, 2013 marks thirty years of research into the geology, geomorphology and mineralogy of Jenolan Caves. The ideas and some of the images presented here have emerged from this extended period of looking, puzzling, looking again and just sometimes seeing the light. Firstly I must acknowledge David Branagan who wrote the magic piece of paper that gained permission for my first research trip to Jenolan in 1983, supervised my PhD, and always thought the caves were old, but as it turned out not old enough.

Many Jenolan people have assisted with fieldwork, paperwork, accommodation, and shared their valuable local knowledge and insights with me. I must particularly thank Ernst Holland, Nigel Scanlan, Andy Lawrence, the late John Callagan, Andrew Fletcher, Stephen Riley, Stephen Meehan, Ted Mathews and Dan Cove in this regard. It is impossible to undertake research in show caves without the cooperation and support of the cave guides and I must thank guides past and particularly guides present for their welcome, assistance and cooperation.

Understanding of Jenolan Caves has been greatly enhanced by collaboration with mineralogy colleagues from the Australian Museum: Ross Pogson and David Colchester and revolutionized by collaboration with dating colleagues from the CSIRO: Horst Zwingmann and Phil Schmidt.

The compilation of this paper has been greatly assisted by the supply of maps and sections by Al Warild, Jenolan Survey Project, and the capture of a missing image by Ted Matthews. My family Penney and Michael have endured and survived my research and with her great eye for detail Penney has read and corrected the drafts of this paper.

REFERENCES

Allan, T.L. (1986). Geology of Jenolan Caves Reserve. BSc Hons thesis, University of Sydney, Sydney.

Bella, P and Bosák, P. (2012). Speleogenesis along deep regional faults by ascending waters: case studies from Slovakia and Czech Republic. *Acta carsologica* **41**, 169-192.

Dunlop, B.T. (1979). 'Jenolan Caves, 11th Edition'. (New South Wales Department of Tourism: Sydney).

House, M. J. (1988). The geology of an area centred on Bulls Creek, Northeast of Jenolan Caves N.S.W. BSc Hons thesis, University of Sydney, Sydney.

Jones, B. (1992). Void-filling deposits in karst terrains of isolated oceanic islands: a case study from Tertiary carbonates of the Cayman Islands. *Sedimentology* 39, 857-876.

Loucks, R.G. (2007). A review of coalesced, collapsed-paleocave systems and associated suprastratal deformation. *Acta carsologica* **36**, 121-132.

McClean, S.M. (1983). Geology and cave formation, Jenolan Caves, N.S.W. B.App.Sc. thesis, N.S.W. Institute of Technology, Sydney.

Osborne, R.A.L. (1984). Lateral facies changes, unconformities, and stratigraphic reversals: Their significance for cave sediment stratigraphy. *Cave Science: Transactions of the British Cave Research Association* **11**, 175-184.

Osborne, R.A.L. (1995). Evidence for two phases of Late Palaeozoic karstification, cave development and sediment filling in southeastern Australia. *Cave and Karst Science* 22, 39-44.

Osborne, R.A.L. (1999a). The inception horizon hypothesis in vertical to steeply-dipping limestone: applications in New South Wales, Australia. *Cave and Karst Science* 26, 5-12.

Osborne, R.A.L. (1999b). The origin of Jenolan Caves: Elements of a new synthesis and framework chronology. *Proceedings of the Linnean Society of New South Wales* 121, 1-26.

Osborne, R.A.L. (2002). Significance and monitoring. *Acta carsologica* 31, 21-33.

Osborne, R.A.L. (2004). Tales from Marble Halls: The geology and geomorphology of Wombeyan Caves. In 'Caves and Karst of Wombeyan' (Ed R. Ellis) pp. 55-71. (Sydney Speleological Society: Sydney).

Osborne, R.A.L. (2005). Dating ancient caves and related palaeokarst. *Acta carsologica* 34, 51-72.

Osborne, R.A.L, (2007). The world's oldest caves: - how did they survive and what can they tell us? *Acta carsologica* 36, 133-142.

Osborne, R.A.L. (2010). Rethinking eastern Australian caves. In 'Australian landscapes'. (Eds P. Bishop and B. Pillans) pp 289-308. Geological Society of London Special Publication 346.

Osborne, R.A.L., Zwingmann, H., Pogson, R. E. and Colchester, D. M. (2006). Carboniferous Clay Deposits from Jenolan Caves, New South Wales, Australia. *Australian Journal of Earth Sciences* 53, 377-405.

Pogson, D. J. and Watkins, J. J. (1998). 'Bathurst 1:250 000 Geological Sheet SI/55-8: Explanatory Notes'. (Geological Survey of New South Wales: Sydney).

Rowling, J. (2004). Studies on aragonite and its occurrence in caves, including New South Wales caves. *Journal and Proceedings of the Royal Society of New South Wales* 137, 123-149.

Sass-Gustkiewicz, M. (1974). Collapse breccias in the ore-bearing dolomite of the Olkusz mine (Crakow-Silesian ore district). *Roczink Polskiego Towarzystwa Geologicznego* 44, 217-226.

Sussmilch, C.A. and Stone, W.G. (1915). Geology of the Jenolan Caves district. *Journal and Proceedings of the Royal Society of New South Wales* 49, 332-348.

Taylor, G. (1923). The Blue (Mountain) Plateau. In 'Pan-Pacific Science Congress, Australia 1923, Guide-book to the Excursion to the Blue Mountains, Jenolan Caves and Lithgow' (Alfred James Kent, Government Printer: Sydney)

Taylor, G. (1958). 'Sydneyside scenery and how it came about'. (Angus and Robertson: Sydney).

van der Beek, P., Pulford, A. and Braun, J. (2001). Cenozoic Landscape Development in the Blue Mountains (SE Australia): Lithological and Tectonic Controls on Rifted Margin Morphology. *The Journal of Geology* 109, 35–56.